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Thermal Simulations of a Silicon Carbide Super Gate Turn-off (SGTO) with Pulsed Power Cycles

by Gregory K. Ovrebo

ARL-MR-0827 August 2012

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14. ABSTRACT We have performed computer simulations of thermal effects in a silicon carbide (SiC) super gate turn-off (SGTO) thyristor caused by short high-power pulses. We used two power pulses of different widths, repeated in multiple duty cycles, as inputs to our model. We used finite element analysis to calculate temperatures in and around the SiC dies during application of the power pulse and in the period between pulses.			
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1. Introduction

The U.S. Army Research Laboratory (ARL) is involved in the development of devices for high-temperature and high-power applications in future Army systems. Silicon carbide (SiC), because of its wide bandgap and enhanced material properties, allows devices to operate at higher power levels and higher temperatures than silicon devices. One such SiC device is a super gate turn-off (SGTO) thyristor designed by Cree, Inc., and the Silicon Power Corporation, which has been evaluated by the Power Conditioning Branch of ARL.

As an adjunct to laboratory evaluations, we have performed simulations of the thermal response of this SGTO to periodic short, high-power pulses. We have constructed a three-dimensional (3-D) model of the device, incorporating the temperature-dependent physical properties of the materials, and calculated the changes in temperature over time as we apply power pulses of two different widths and peak power levels to the SiC die. The power pulses were repeated in duty cycles of 1%, 5%, and 25%. We plot graphs of temperatures in the active portion of the die calculated during the simulation of 20 or 30 power cycles and show contour plots of the model's surface temperature at selected time intervals in the simulation.

2. Model Preparation

Figure 1 shows a view of our 3-D model of the SiC SGTO, including the plastic package around the die. This model was created with SolidWorks 3-D computer-aided design (CAD) software. The package holds four SiC dies, shown in this figure with copper pads on the top surface.

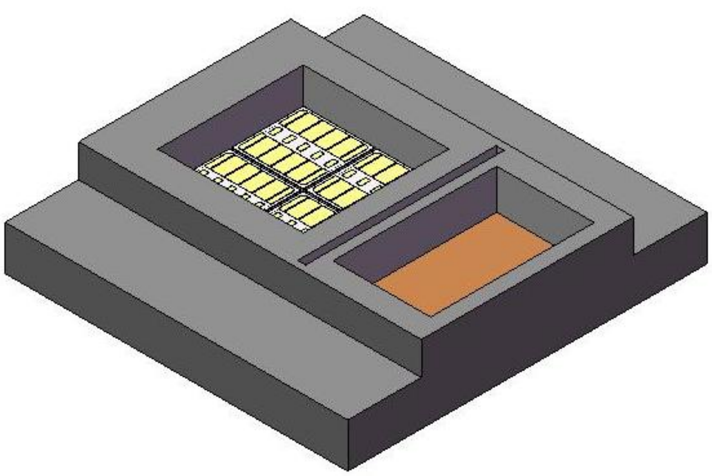

Figure 1. Three-dimensional model of the SiC SGTO package and die.

Unfortunately, the full 3-D model is awkward to deal with in finite element analysis. When the model is broken down into a mesh, we have to spend a great deal of time and memory computing the status of parts of the package that have little influence on the temperature of the dies. We can simplify matters by ignoring the plastic case in our model and performing the simulation on the baseplate and SiC dies alone, with little loss of accuracy in calculated temperature distributions. The simplified model used in our simulations is shown in figure 2.

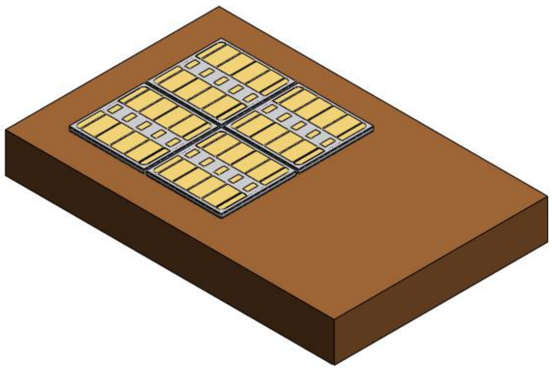

Figure 2. Simplified model of the SiC SGTO without the plastic package.

Figure 3 shows the mesh of the model used in our simulations. Note that we applied a finer mesh to the die and underlying layers than to the baseplate. This assures us that the thin layers in the device are properly included in the thermal transfer calculations; with a coarser mesh, these material layers might not register properly. It also increases the spatial resolution of our calculated temperature distributions.

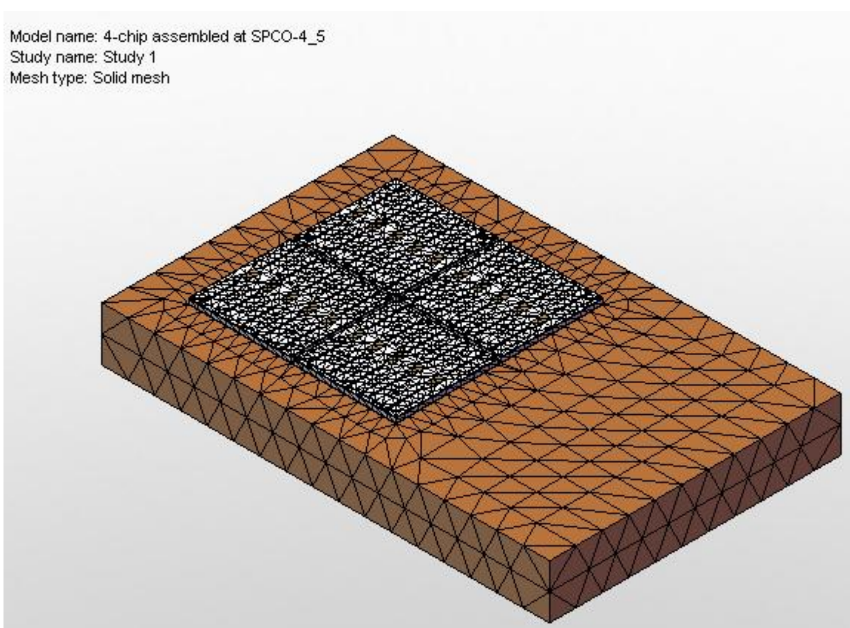

Figure 3. Mesh used in thermal simulation of the SiC SGTO.

3. Thermal Simulations

We performed thermal simulations using two power pulses of different durations and peak power levels. The first pulse was 1 ms wide with a peak power level of 36 kW. The second pulse was 0.165 ms wide with a peak power level of 129 kW. Each pulse was simulated in duty cycles of 1%, 5%, and 25%. The power levels specified were the total power applied to all four dies combined. The power pulse was described in our simulation by a text file of power levels and corresponding times, which became our heat input in SolidWorks Simulation. Each cycle of the simulation was broken down into separate heating and cooling phases, and each phase divided into about 10 equal time steps. The temperature distribution in the meshed model was calculated at each time step.

3.1 Wide Pulse Simulations

Figure 4 shows a graph of the 1-ms-wide power pulse used as a power input in our first simulation of thermal effects in the SiC SGTO. A peak power of 9 kW was applied to each of the four dies in the SGTO. The forward voltage drop was 10 V and the peak current was 3600 A in the four dies combined. As a boundary condition, the initial temperature of the SGTO was defined to be 20 °C. To imitate the effect of mounting the SGTO on a coldplate, the bottom surface of the baseplate was defined to be a constant 20 °C.

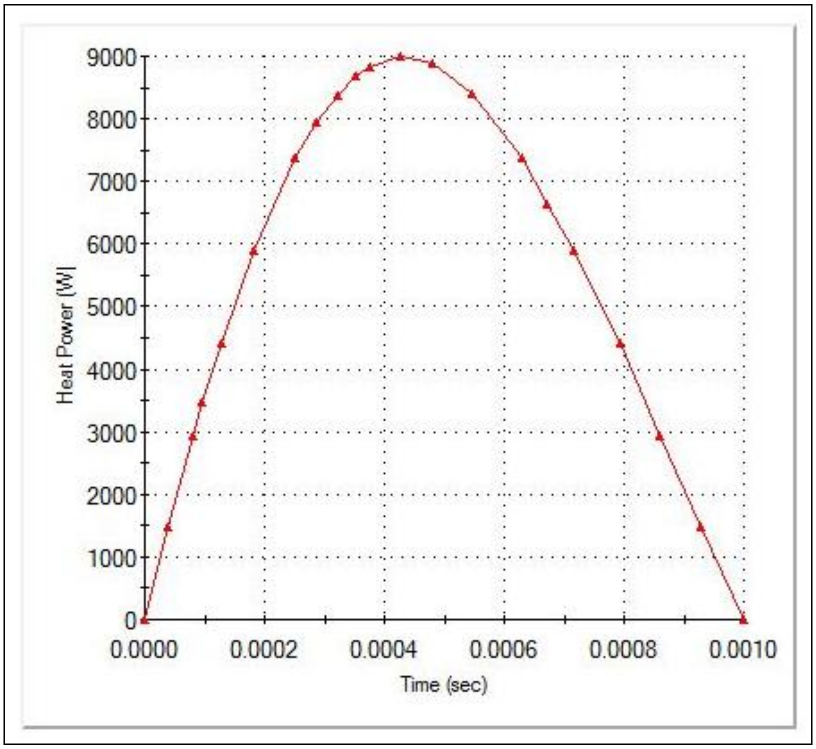

Figure 4. The 1-ms-wide power pulse specified as an input on the SiC dies.

This power pulse was first used to simulate a 1% duty cycle. Figure 5 shows a plot of the calculated change in average temperature in the SiC die over the first 12 cycles. One can see that at this low rate of repetition, the devices reach a maximum temperature after just a few cycles.

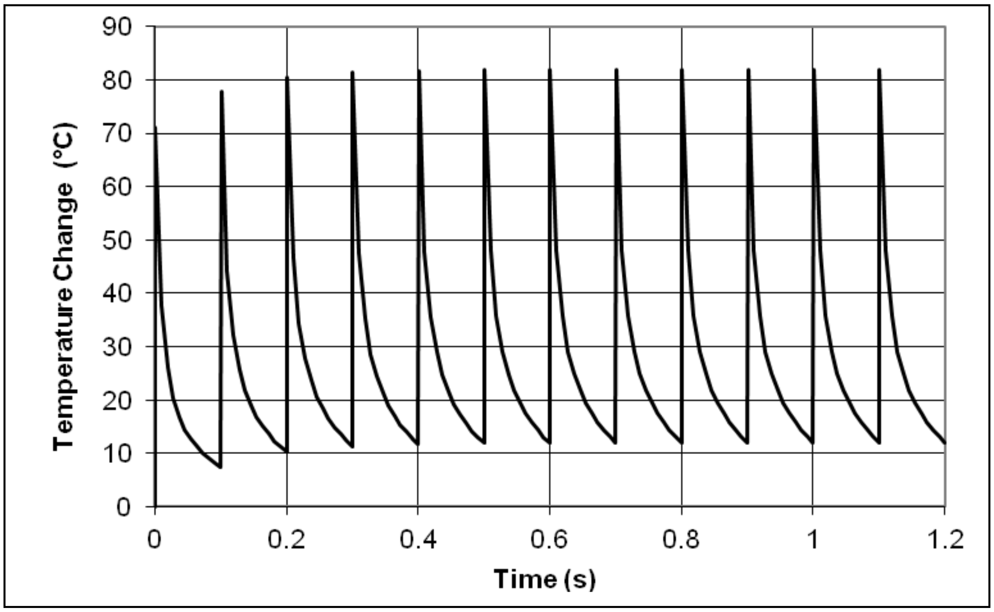

Figure 5. Change in average temperature in the SiC die at a 1% duty cycle of the 1-ms pulse.

Figure 6 is a contour plot of temperatures on the surface of the SGTO at the end of pulse number 12 (t = 1101 ms). Figure 7 shows surface temperatures 99 ms later, at the end of the 12th cycle (t = 1200 ms).

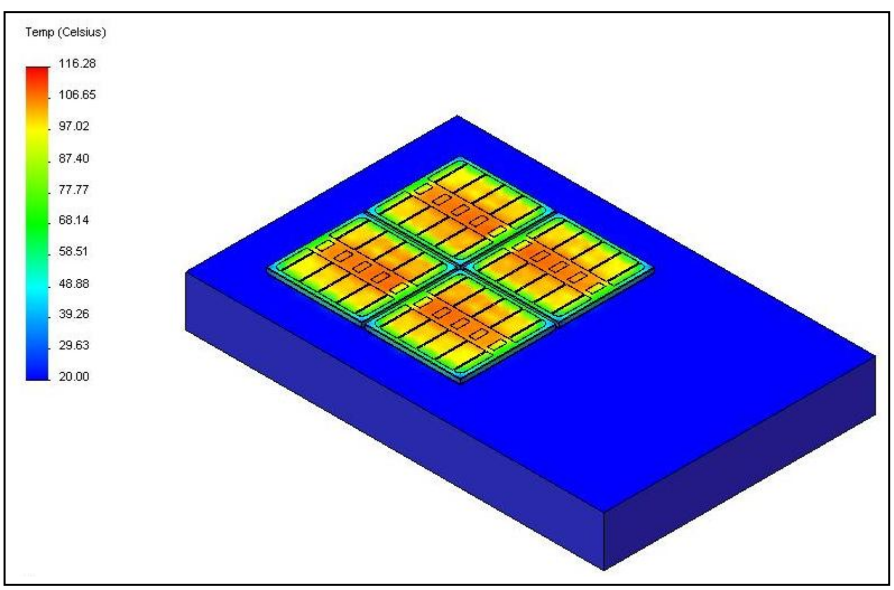

Figure 6. Temperatures on the SGTO at the end of the 12th pulse, 1% duty cycle.

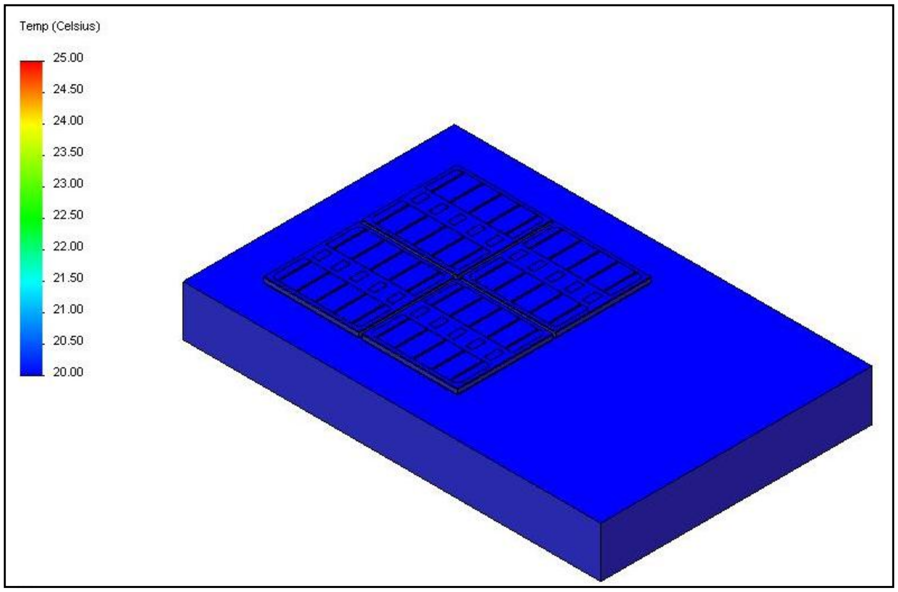

Figure 7. Temperatures on the SGTO after cooling for 99 ms after pulse 12, 1% duty cycle.

We next looked at the 1-ms pulse when used in a 5% duty cycle. Figure 8 shows a graph of the average temperature change in the active part of the SiC dies over 20 cycles. At the end of 20 cycles, we can see equilibrium is established, where the peak temperature has reached a maximum value in each cycle.

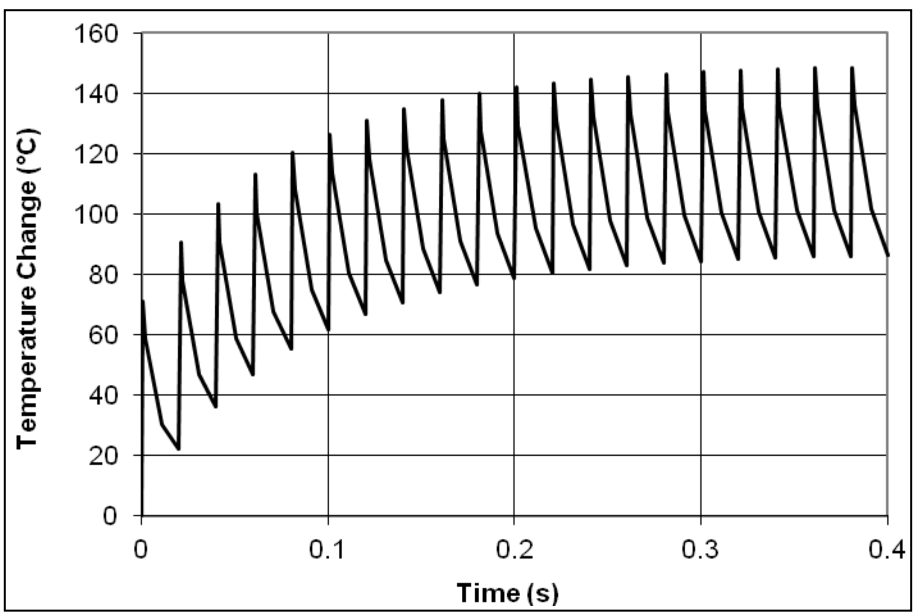

Figure 8. Average temperature change in the SiC die over 20 cycles of the 1-ms pulse in a 5% duty cycle.

Figure 9 shows a contour plot of temperatures on the surface of the SiC SGTO at the end of the 20th pulse in the 5% duty cycle, where temperatures in the device are at their maximum. Figure

10 shows temperatures on the SGTO at the end of cycle 20, after it has cooled for 19 ms after the 20th pulse.

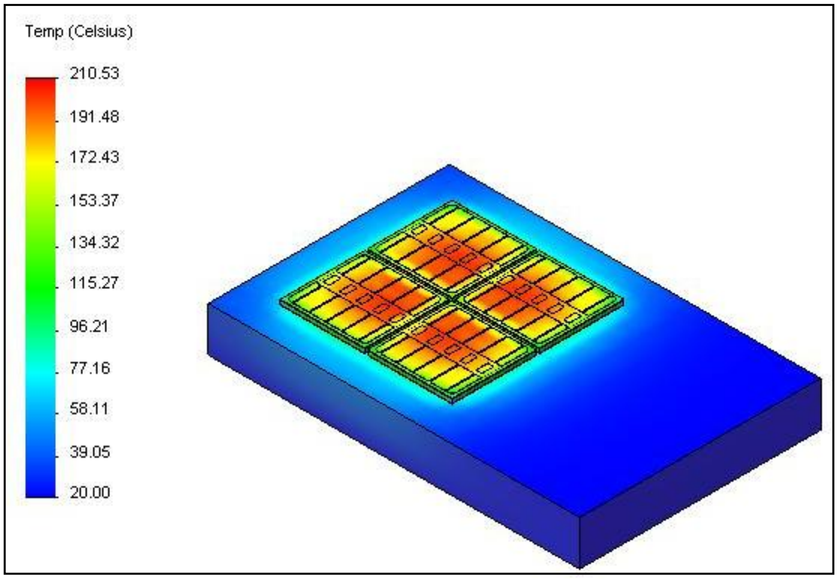

Figure 9. Temperatures on the SiC SGTO at the end of the 20th pulse of the 5% duty cycle, 1-ms pulse.

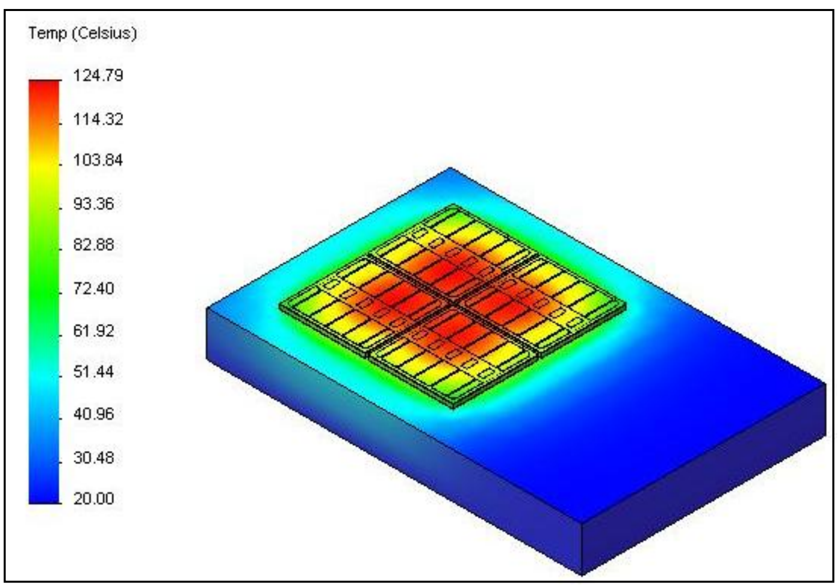

Figure 10. Temperatures on the SiC SGTO at the end of the 20th cycle of the 5% duty cycle, 1-ms pulse.

Figure 11 is a graph of the temperature change in the active part of the die during a 25% duty cycle. After 20 cycles, the temperature during the pulse has not yet reached equilibrium.

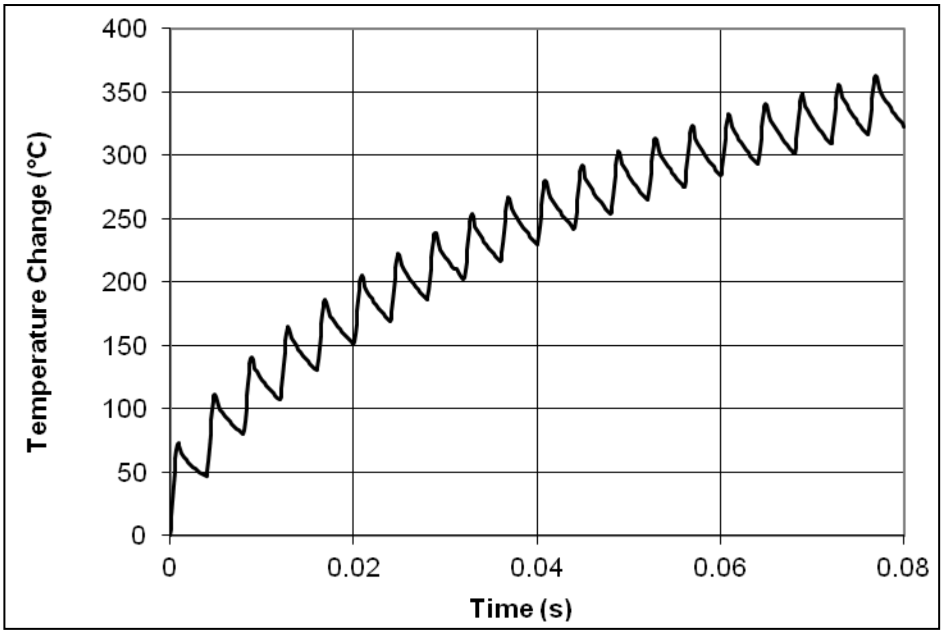

Figure 11. Average temperature change in the SiC dies during the 25% duty cycle, 1 ms pulse.

Figure 12 shows the temperature contours on the SiC SGTO immediately after the 20th pulse; figure 13 shows the temperatures on the SGTO 3 ms later, at the end of cycle 20.

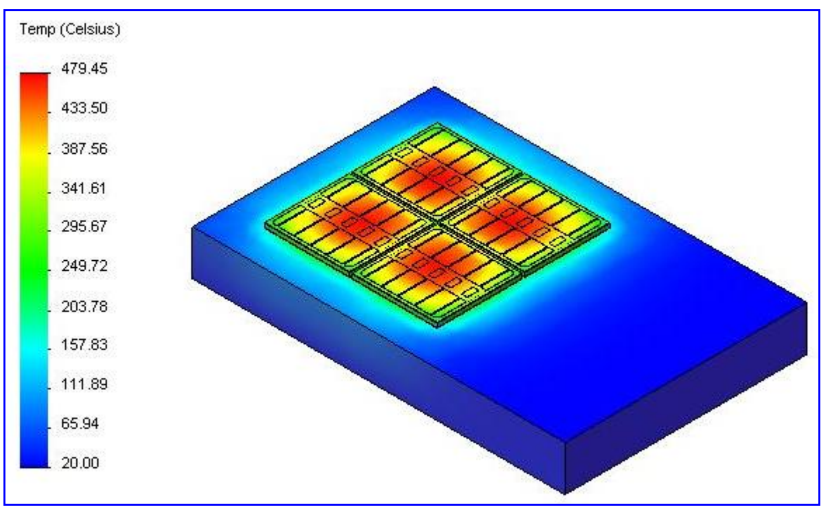

Figure 12. Temperatures on the SGTO module after pulse 20, 25% duty cycle, 1-ms pulse.

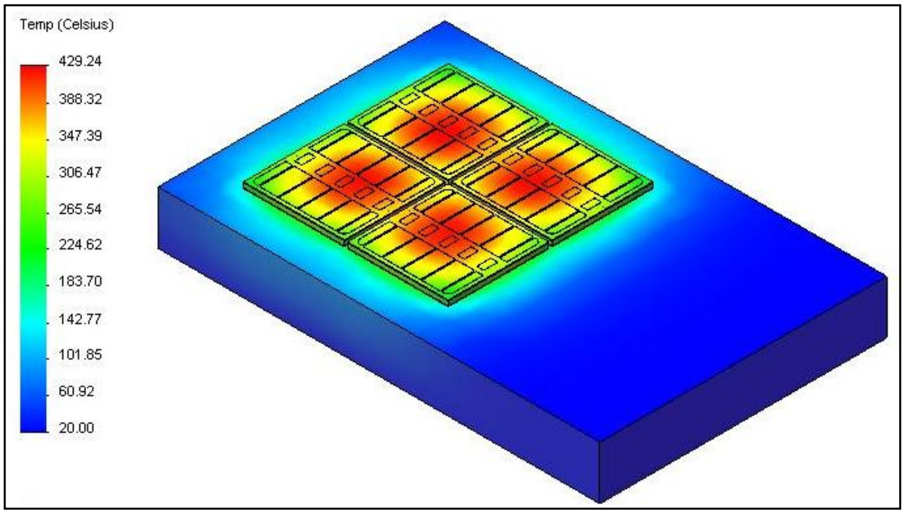

Figure 13. Temperatures on the SGTO module at the end of cycle 20, 25% duty cycle, 1-ms pulse.

3.2 Narrow Pulse Simulations

The next series of thermal simulations used a narrower pulse with a higher peak power than our first simulation. The 0.165-ms-wide pulse shown in figure 14, with a peak power of 32 kW, was applied to each of the four SGTO dies in the package. The maximum forward voltage drop is 16 V and the peak current is 8250 A in the four dies combined. Each marker in the graph represents a point in the number file used as a thermal input in our SolidWorks simulation. As in the first simulation, we defined an initial temperature of 20 °C and a constant baseplate temperature of 20 °C.

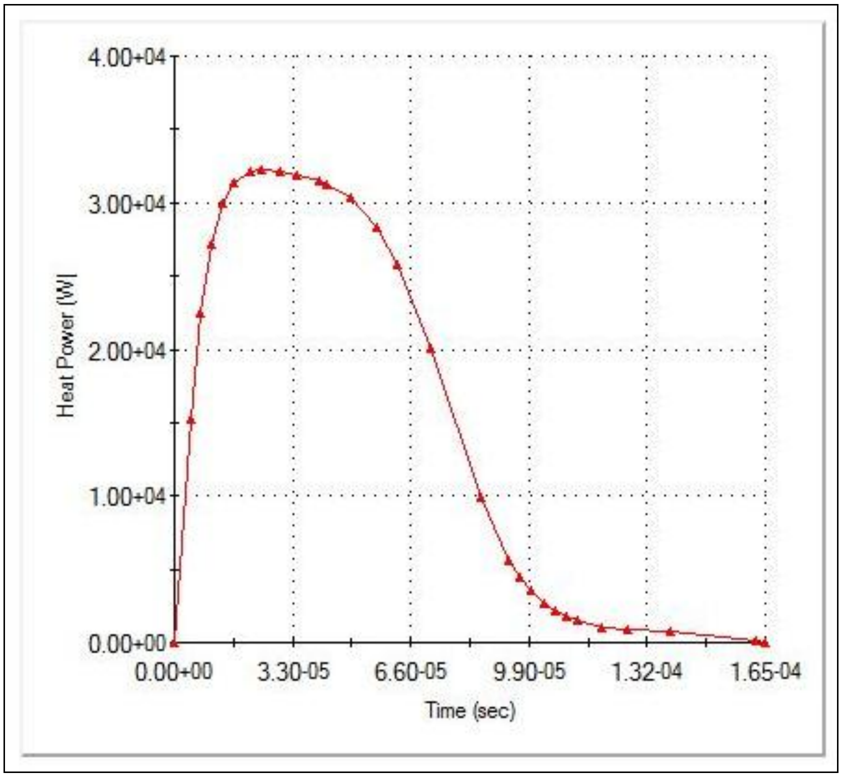

Figure 14. Plot of the narrow power pulse (0.165 ms wide) used as heat input to the second series of thermal simulations.

Figure 15 is a graph of the temperature changes in the SiC dies during the first 25 cycles of the 1% duty cycle. At this low rate of repetition, the peak temperature in each cycle has reached a maximum.

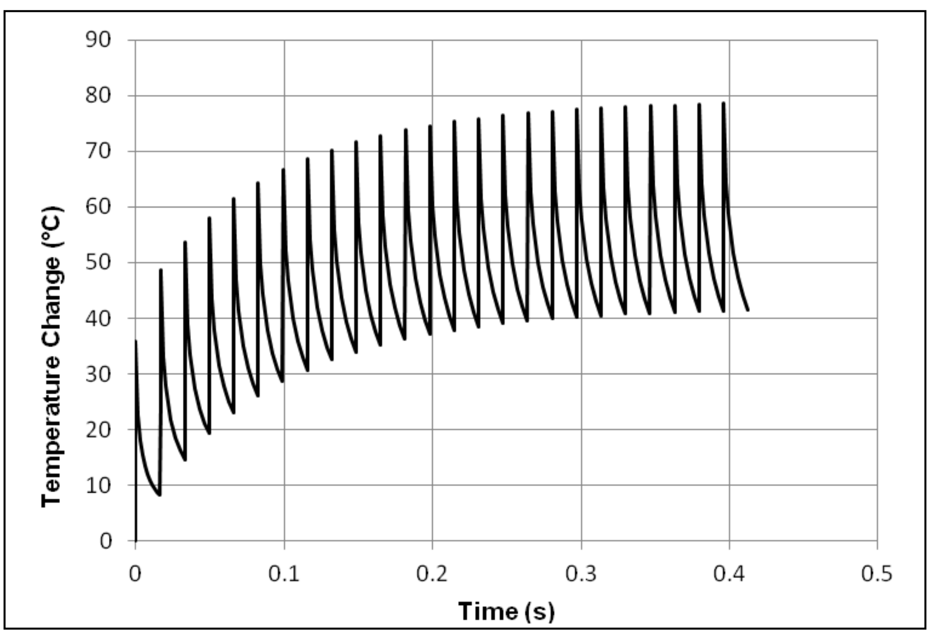

Figure 15. Temperature change in the SiC dies during the 1% duty cycle, 0.165-ms pulse.

Figure 16 shows the distribution of temperatures on the surface of the SGTO at the end of pulse 25, when temperatures are near a maximum. Figure 17 shows temperatures on the SGTO 16.3 ms later, at the end of the “off” part of cycle 25.

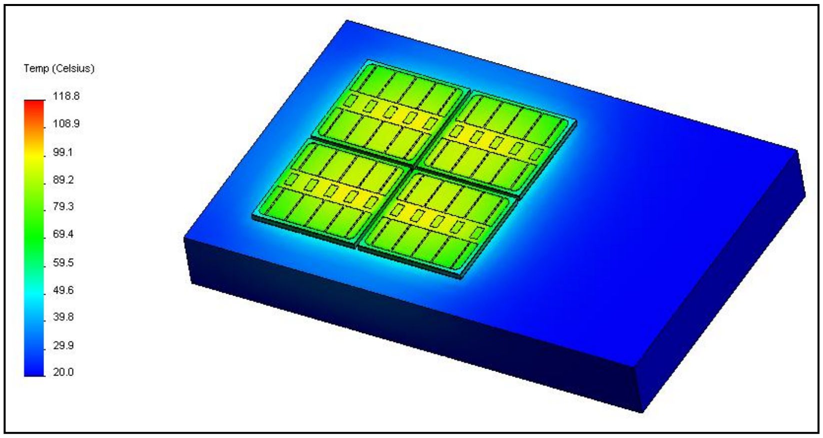

Figure 16. Temperatures on the SGTO at the end of pulse 25, 1% duty cycle, 0.165-ms pulse.

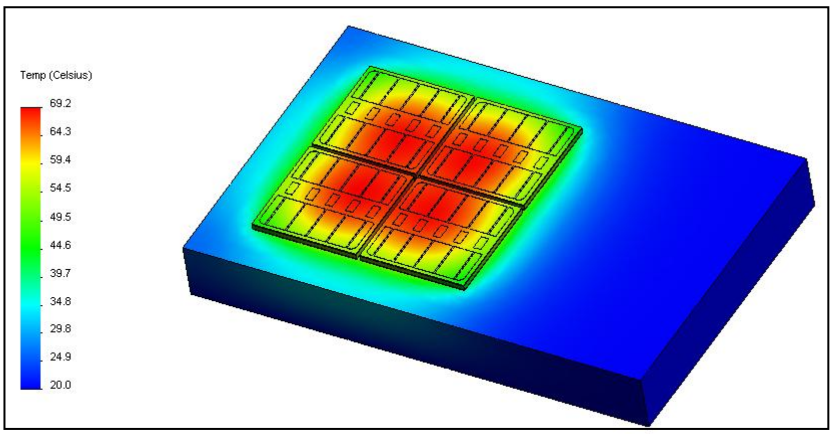

Figure 17. Temperatures on the SGTO at the end of cycle 25, 1% duty cycle, 0.165-ms pulse.

Figure 18 is a graph of temperature changes in the SiC dies over 40 cycles with the narrow power pulse at a 5% duty cycle. Temperatures in the SiC thyristors exceed 200 °C after 40 cycles, and the temperatures are still climbing, although the curve shows signs of flattening.

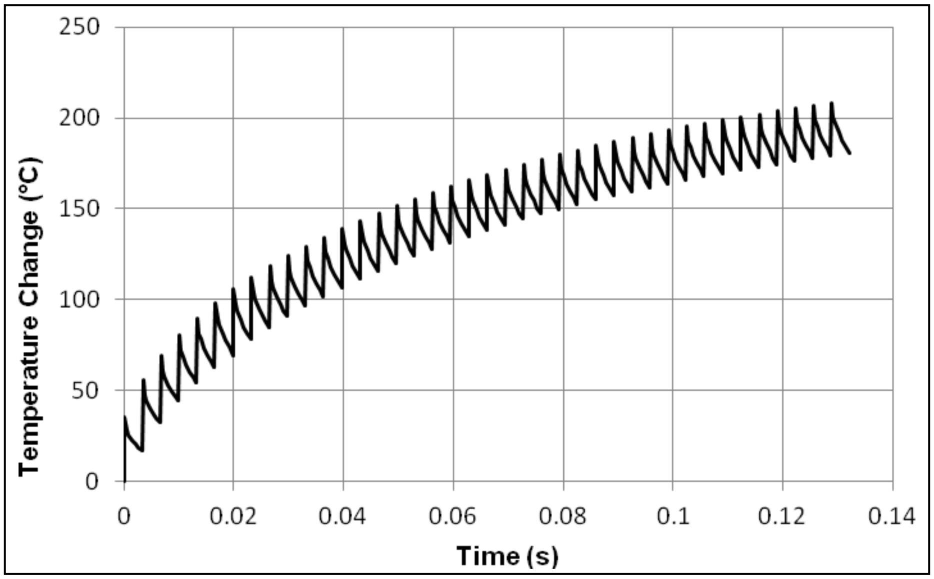

Figure 18. Temperature increases in the SiC dies during the 5% duty cycle, 0.165-ms power pulse.

Figure 19 is a plot of temperatures on the SGTO module at the end of pulse 25. Figure 20 shows temperatures on the module 3.1 ms later, at the end of cycle 25.

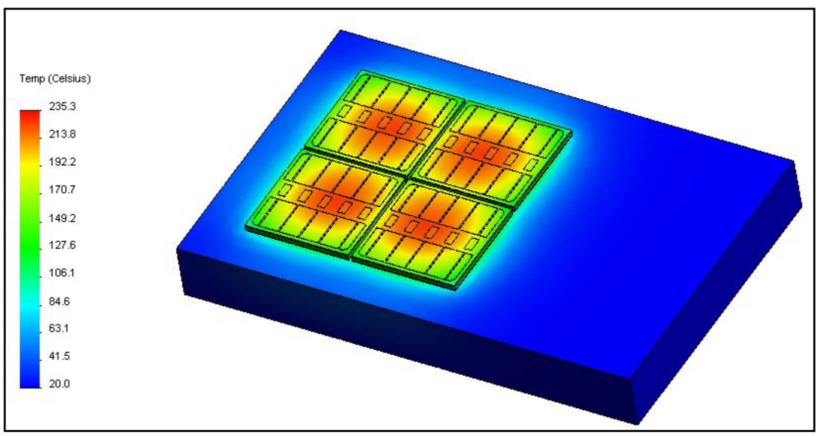

Figure 19. Temperature contour plot at end of pulse 25, 5% duty cycle, 0.165-ms pulse.

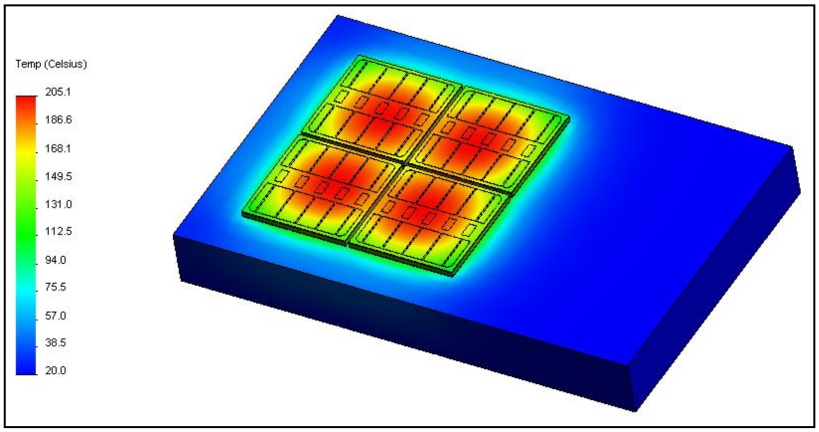

Figure 20. Temperature contour plot at end of cycle 25, 5% duty cycle, 0.165-ms pulse.

Figure 21 is a graph of temperature changes in the active part of the SiC dies during the 25% duty cycle of the 0.165-ms pulse. Thirty cycles are shown, during which temperatures have risen to levels at which the devices will sustain damage.

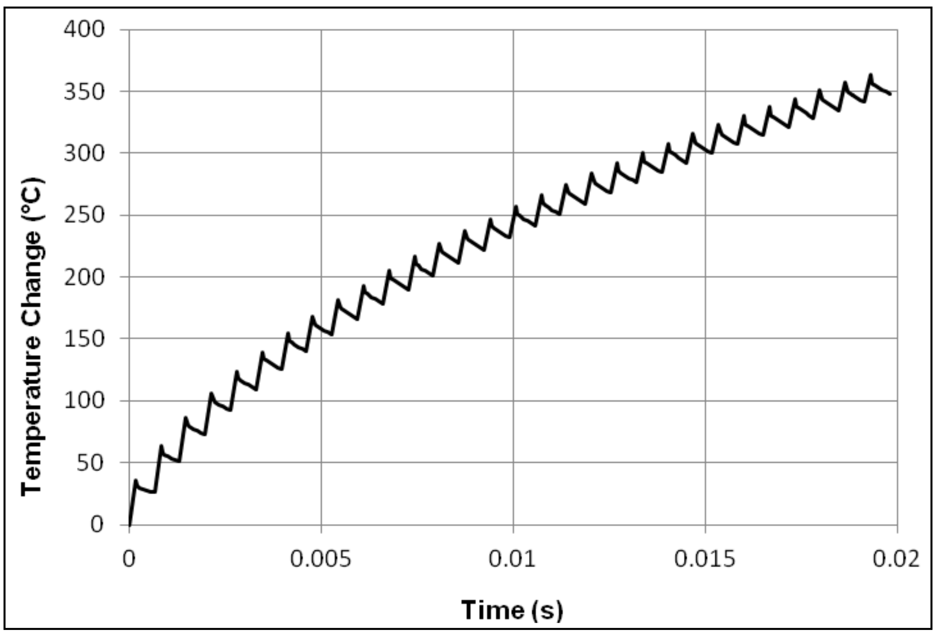

Figure 21. Temperature increases in the SiC dies during 25% duty cycle, 0.165-ms power pulse.

Figure 22 is a temperature contour plot of the SGTO at the end of the 25th pulse. Figure 23 shows temperatures on the module about 0.5 ms later, at the end of the 25th cycle.

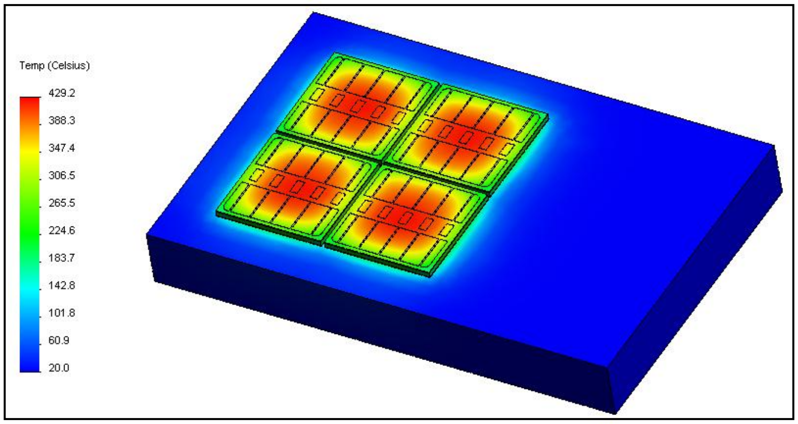

Figure 22. Temperatures on the SGTO at the end of pulse 25, 25% duty cycle, 0.165-ms pulse.

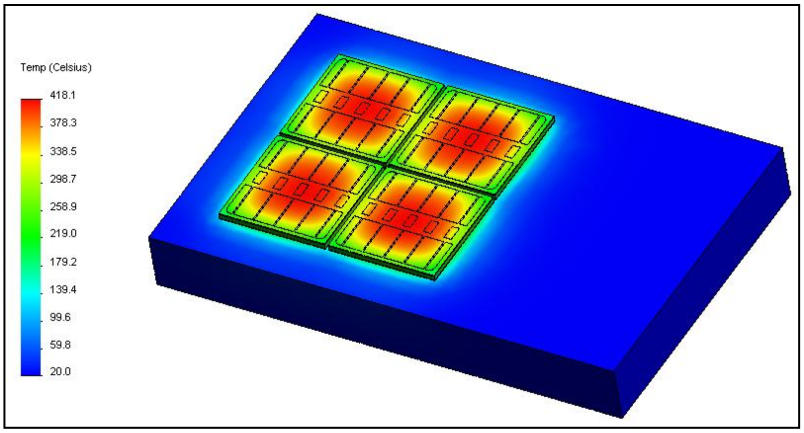

Figure 23. Temperatures on the SGTO at the end of cycle 25, 25% duty cycle, 0.165-ms pulse.

4. Conclusions

We performed calculations of thermal effects in a SiC SGTO driven by cyclical high power pulses. When the wide pulse (1 ms wide) and narrow pulse (0.165 ms wide) are repeated in a 1% duty cycle, the SGTO reaches a thermal equilibrium within 10 cycles. The peak average temperature increase calculated in the die is approximately 60 °C.

When the duty cycle of the wide pulse increases to 5%, the SGTO die reaches equilibrium within 20 cycles; the maximum temperature increase is 130 °C. When the narrow pulse is repeated at a 5% duty cycle, the SGTO did not reach equilibrium within the 40 cycles of our simulation, although the temperature curve did show a decreasing slope. The temperature in the SiC die had increased almost 200 °C above the initial temperature; extended operation at this duty cycle might result in impaired device function or damage.

When the SGTO was simulated at a 25% duty cycle, peak temperatures in the SGTO rose more than 300 °C within 30 cycles and showed little sign of moderating. At those temperature levels, solder attaches would melt, SiC dies would be damaged, and the SGTOs would not survive.

By performing time-dependent simulations of thermal effects in 3-D models incorporating the physical properties of SiC and other materials, we are able to make predictions about the temperature levels in an SGTO under various operating conditions without subjecting the devices to the stresses of laboratory testing. We avoid damage to devices, which, in their developmental stages, may be somewhere between scarce and irreplaceable.

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